Subject: Fwd: [Atmos-fiscstaff] Final report for for N00014-11-1-0331 (UW Ref A62168, BN 62-2173)
From: Andrew Sattler <acs29@uw.edu>
Date: 11/9/2017 1:49 PM
To: ONR_Seattle@onr.navy.mil
CC: closeout <closeout@uw.edu>, Dale Durran <drdee@uw.edu>, "'fiscstaff@atmos.washington.edu'" <FiscStaff@atmos.washington.edu>

Please find attached the final report on N00014-11-1-0331 (UW Ref A62168, BN 62-2173) submitted to the ONR technical contact yesterday (shown below).

A copy of this email will be include with hard copy cc's to the following as required in the award documents:

Defense Technical Information Center
8725 John J Kingman Road Ste 0944
Fort Belvoir, VA 22060-6218

Naval Research Laboratory
ATTN: CODE 5596
4555 Overlook Avenue SW
Washington, DC 20375-5320

If there are any further items needed to close out this award, please let us know.

Best Regards,

Andrew

Andrew Sattler
Grants Manager
Department of Atmospheric Sciences
University of Washington
phone 206-543-7842
fax 206-543-0308
acs29@atmos.uw.edu

-------- Forwarded Message --------
Subject:[Atmos-fiscstaff] Final report for for N00014-11-1-0331
Date: Thu, 9 Nov 2017 10:57:50 -0800
From: Dale Durran <drdee@uw.edu>
To: Ron Ferek <ron.ferek@navy.mil>
CC:fiscstaff@atmos.washington.edu

Hi Ron,

Here is my final report for N00014-11-1-0331.

Thanks,

Dale

— Attached Message Part —

Dale Durran, Professor and Chair
Atmospheric Sciences
Box 351640
University of Washington
Seattle, WA 98195

Phone: (206) 543-7440
Email: drdee@uw.edu
www.atmos.washington.edu/~durrand/

— Attached Message Part —

— Attachments: —

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14. ABSTRACT
One of the major efforts in the atmospheric sciences has been to develop and implement high-resolution forecast models and to improve their parameterization of unresolved physical processes. For the last three decades, the relatively pessimistic predictions of Lorenz (1969) about the predictability of small-scale (i.e., mesoscale) atmospheric features have been largely ignored as routine weather forecasts were conducted at increasingly fine scale. Recent research suggests there are nevertheless, significant limitations to the predictability of mesoscale atmospheric circulations. Our goal is to develop an understanding of the predictability of such circulations in state-of-the-art forecast models.

15. SUBJECT TERMS
Predictability, numerical weather forecasting

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Final Report: Characterization of Mesoscale Predictability

Dale R. Durran
University of Washington
Department of Atmospheric Sciences
Box 351640
Seattle, WA 98195-1640
phone: (206) 543-7440 fax: (206) 543-0308 email: durrand@atmos.washington.edu

Award Number: N00014-11-1-0331
http://www.atmos.washington.edu/~durrand/

LONG-TERM GOALS

One of the major efforts in the atmospheric sciences has been to develop and implement high-resolution forecast models and to improve their parameterization of unresolved physical processes (boundary-layer transport, cloud microphysics…). For the last three decades, the relatively pessimistic predictions of Lorenz (1969) about the predictability of small-scale (i.e., mesoscale) atmospheric features have been largely ignored as routine weather forecasts were conducted at increasingly fine scale. Recent research suggests there are nevertheless, significant limitations to the predictability of mesoscale atmospheric circulations. Our goal is to develop an understanding of the predictability of such circulations in forecasts generated by state-of-the-art high-resolution mesoscale models.

OBJECTIVES

Specific questions addressed in our research include:

1. How commonly does rapid growth of initial errors occur in mesoscale meteorological settings?
2. How sensitive are these results to different strategies for developing the initial ensemble spread using the ensemble Kalman filter?
3. How can ensemble forecasts be best used to identify and help predict these difficult events?

The answers to these questions are of direct benefit to Navy forecasters using COAMPS to produce aviation and other forecasts of mesoscale phenomena.

APPROACH

The P.I. and graduate student Matt Gingrich, together with Drs. James Doyle and P. Alex Reinecke of NRL, are using the COAMPS model to conduct 100-member ensemble simulations of high impact events. Under previous support we considered downslope windstorms (Reinecke and Durran, 2009), which, it had been argued, had high mesoscale predictability. More recently, we have considered the prediction of lowland snow in the Puget Sound lowlands. Both of theses weather phenomenon have exhibited high sensitivity to initial conditions in the sense that the spread within a large initial ensemble (either 70 or 100 members) grew vary rapidly over time scales much shorter than anticipated. Part of the motivation for this effort is to help inform the community of the need to move beyond

deterministic mesoscale forecasts, which despite all the talk about ensemble prediction, are still the backbone of military, civilian and private meteorological forecasts.

WORK COMPLETED

Our paper "Large-Scale Errors and Mesoscale Predictability in Pacific Northwest Snowstorms" (written in collaboration with James Doyle and Alex Reinecke), was published in the *Journal of the Atmospheric Sciences*. A second paper, "Atmospheric Predictability: Why Butterflies Are Not of Practical Importance," by the P.I. and graduate student Mark Gingrich has appeared in the *Journal of the Atmospheric Sciences*. Mark completed his master's thesis entitled Mesoscale Predictability and Error Growth in Short Range Ensemble Forecasts" and also presented these results at the American Meteorological Society conference on Mesoscale Meteorology in August 2013 in Portland, Oregon.

RESULTS

The growth of mesoscale-forecast errors arising from uncertainties in initial conditions was investigated by examining 100-member ensemble forecasts of two powerful snowstorms that struck the East Coast of the United States in February and December 2010. Our most exciting and significant results over the last year connect the behavior of the spread in ensemble errors due to initial condition uncertainty with error growth in these two complex state-of-the-art ensemble forecasts with the classical turbulence-model theory of predictability proposed by Lorenz (1969).

Many previous studies have aimed to elucidate the error growth dynamics controlling mesoscale predictability. Important early theories were based on an inverse error cascade in classical turbulence models, where unresolved small-scale errors gradually propagated up to the largest scales Lorenz (1969). In contrast, the dominant paradigm in operational mesoscale meteorology has been one in which the mesoscale is assumed to inherit predictability from the synoptic scale and thereby maintain forecast skill at much longer lead times than those suggested by turbulence models (Anthes 1985, Mass 2002). Nevertheless, the results of this research, along with several recent studies (Nuss and Miller 2001, Reinecke and Durran 2009, Durran et al. 2013), suggest that mesoscale circulations are in fact extremely sensitive to small synoptic-scale errors. A variety of situations have now been documented in which the degree of synoptic-scale accuracy required to successfully forecast mesoscale weather patterns at one- or two-day lead times would be quite difficult to achieve in practice.

Recent studies have suggested that forecast errors amplify by projecting onto the most rapidly growing physical structures, the scale of which depends on the model resolution and the dynamics of the flow being modeled. Examples include baroclinic instability on the synoptic scale (Tribbia and Baumhefner 2004) and convective instability on the small scale (Hohenegger and Schär 2007). Linking instabilities with upscale error growth, (Tan et al. 2004; Zhang et al. 2007) suggested a multistage process in which errors originating on the scale of moist convection are responsible for stimulating error growth at intermediate scales that subsequently spread to scales large enough to influence baroclinic instability.

The spectral structure of the ensemble spread in the East-Coast snowstorm forecasts was examined by evaluating the ensemble- and meridional-averaged total and perturbation kinetic energy spectra on the highest resolution 5-km, convection-permitting inner grid. The ensembles clearly captured the observed $k^{-5/3}$ total kinetic energy spectrum at wavelengths less than approximately 400 km and also showed a transition toward a roughly k^{-3} dependence at longer wavelengths. In contrast to the small-scale initial errors assumed in several idealized studies of atmospheric predictability, the initial

perturbation kinetic energy of our EnKF-generated ensembles was maximized at the largest scales. This is consistent with previous investigations that relied on data assimilation to either create pairs of different initial conditions (Bei and Zhang 2007, Mapes et al. 2008) or to initialize a large ensemble (Durran et al. 2013), all of which also found that the initial perturbation kinetic energy was maximized at the largest scales. As discussed in Durran et al. (2013), this large-scale maximum is likely a reflection of both small shifts in the structure of the synoptic-scale waves and the spectral signature of isolated, small-scale disturbances.

At least as notable as the initial structure of the perturbation kinetic energy in our ensembles is the nature of the error growth. As shown in Fig. 3, initial-condition errors did not simply propagate upscale according to an inverse cascade. Instead, the initial errors began growing immediately at all scales, and the amplifying perturbation kinetic energy spectra formed a series of self-similar curves over all wave numbers where the error had not yet saturated. Following the terminology suggested by Mapes et al. (2008), the evolution of the perturbation kinetic energy in Fig.~17 may be described as ``up-magnitude" rather than ``up-scale".

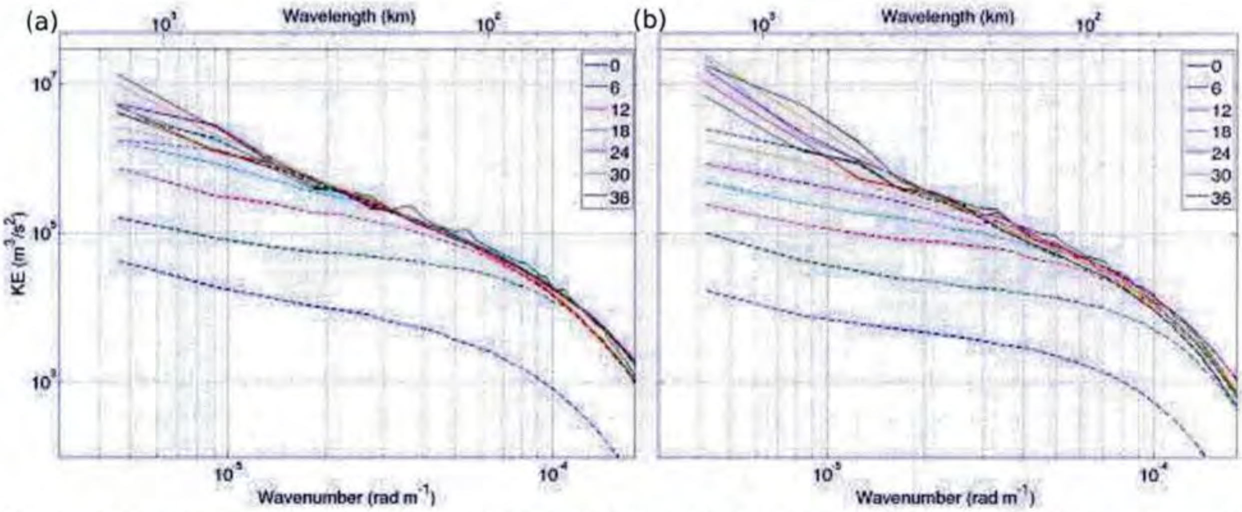

Fig. 1: Ensemble- and meridionally-averaged total (solid lines) and perturbation (dashed lines) kinetic energy spectra at 500 hPa shown every six hours (line colors given in the legend) for the ensemble initialized (a): 12 UTC 4 February and (b): 12 UTC 25 December. Only those wavelengths greater than the 7Δx numerical dissipation scale are shown

The error growth in Fig. 1 can be contrasted with the error growth in typical experiments with the Lorenz (1969) model. Fig. 2 shows the evolution of the error energy spectrum for the Lorenz model at nondimensional times in the interval [0,1]. The initial error is entirely in the smallest scale in Fig. 2a and is white noise in Fig. 2b. In both cases the error at the smallest scale is saturated, and this error expands up-scale as progressively longer wavelengths become saturated. The errors remain small in those scales that are not yet saturated.

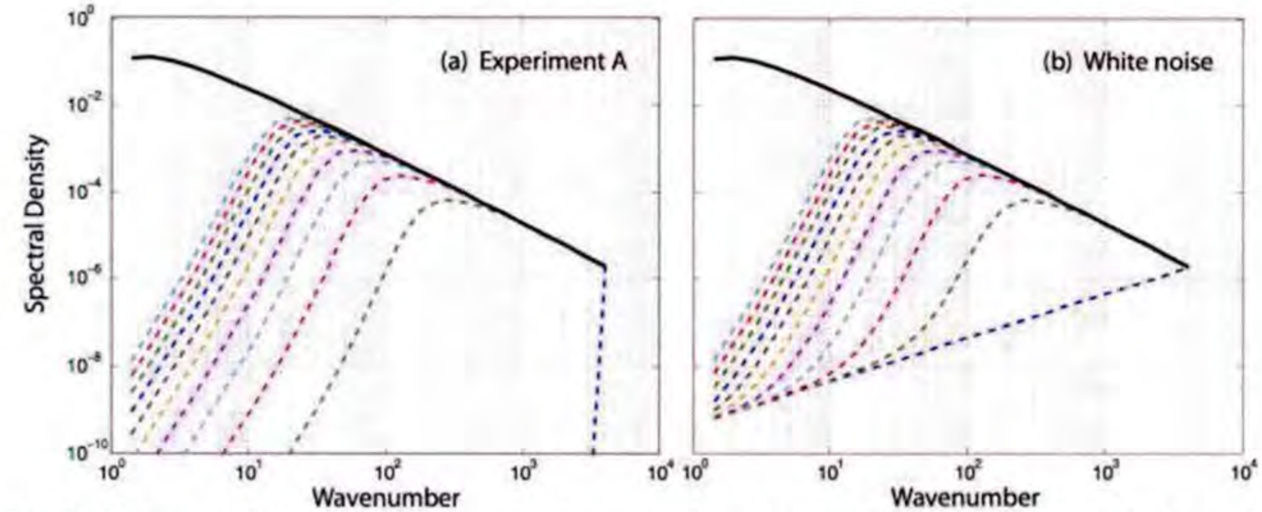

Fig. 2: KE' spectral density as a function of wavenumber k at non-dimensional times t=0 (blue), 0.1 (green),…, 1.0 for initial error saturated at the largest wavenumber (shortest wavelength) and (a) zero elsewhere, or (b) following a white noise spectrum.

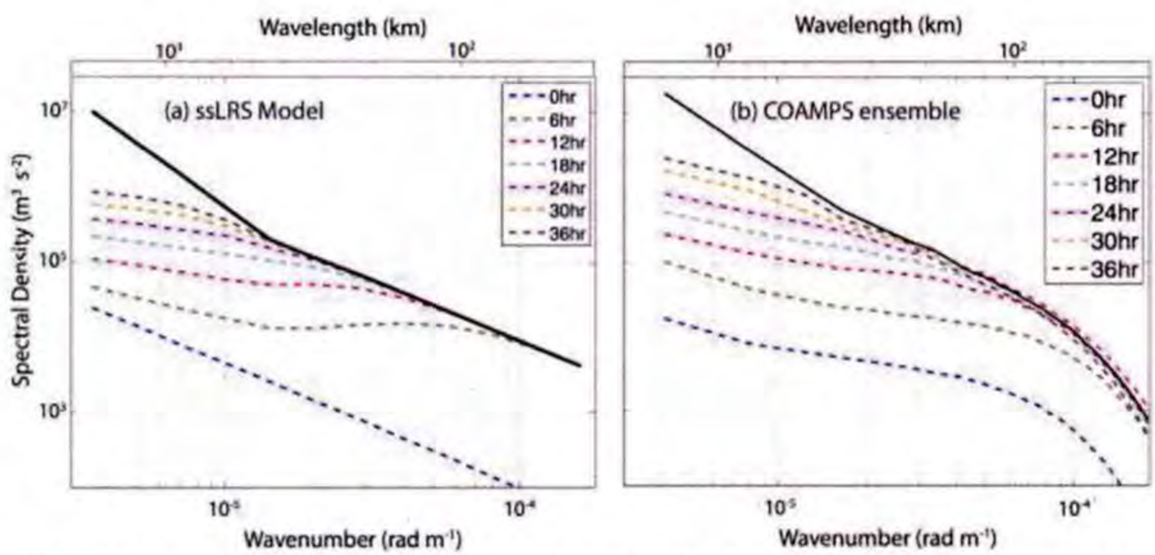

Fig. 3: (a) KE' spectral density as a function of wavenumber k for the modified Lorenz model every 6 hours (line colors given in the legend); black curve shows the saturation spectrum. (b) identical to Fig 1b, except that the curves for the total kinetic energy spectral density at each individual time are replaced by their average over hours 12-36 and plotted as the heavy black line.

The evolution of the KE' spectral density in our improved dimensional version of Lorenz's model (the ssLRS model) and the COAMPS ensemble forecast from 12 UTC 25 December 2010 are compared in Fig. 3. Given the extreme simplicity of the ssLRS model (only 24 degrees of freedom), the agreement with the COAMPS ensemble is surprisingly good, with relatively similar orientations and growth of the KE' density spectra toward the saturation kinetic energy spectrum at all times greater than 6 hours. It should be emphasized that the time scale was not set directly, but rather is determined from observed

values for the legnth and energy scales. The good agreement has provided empirical justification for the use of the ssLRS model to study the importance of small-scale initial errors.

As originally noted, but then largely overlooked by Lorenz, rapid downscale error propagation that also occurs in systems with $k^{-5/3}$ kinetic energy spectra. Very small initial errors in the large scales rapidly propagate downscale to the shortest retained wavelengths. The errors in the shortest wavelengths saturate, and after a brief period the subsequent upscale error growth is similar to what would have occurred if the error was limited to the smallest scales at the outset. *Since the background saturation kinetic energy density is much bigger at longer wavelengths, very small **relative** errors in the large scales can have the same impact on predictability as saturated errors in the small scales.*

,IMPACT/APPLICATIONS

Forecasting mesoscale meteorological phenomena is of importance to many naval operations, including those in coastal zones, those involving aviation in complex terrain, and those requiring information about the structure of the planetary boundary layer. Understanding the degree of confidence that can be realistically expected from fine-scale deterministic weather forecasts at various lead times will help meteorologists and other users assess the importance of alternative approaches, such as ensemble forecast systems. The possibility that small initial errors in the large-scale analysis impose a practical limit on mesoscale predictability is a new paradigm that will provide a further impetus wider adoption of the ensemble approach.

RELATED PROJECTS

ONR Award Number: N000141410287 to the P.I. builds on these results by continuing the investigation of mesoscale predictability.

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PUBLICATIONS

Durran, D.R., P.A. Reinecke, and J.D. Doyle, 2013: Large-Scale Errors and Mesoscale Predictability in Pacific Northwest Snowstorms. *J. Atmos. Sci.*, 70, 1470-1487 [published, refereed]

Durran, D.R. and M.A. Gingrich, M.A., 2014: Atmospheric Predictability: Why Butterflies Are Not of Practical Importance. *J. Atmos. Sci.*, 71, 2476-2488. [published, refereed]

HONORS/AWARDS/PRIZES

"Atmospheric Predictability: Why Butterflies Are Not of Practical Importance." by the P.I. and graduate student Mark Gingrich is currently ranked as number one on the American Meteorological Society's list of the "Top 10 Most Read *JAS* Articles" over the last 12 months.
(See list at http://journals.ametsoc.org/loi/atsc)